DMIC Technical Note
June, 1964

FIRE HAZARDS ASSOCIATED WITH THE USE OF TITANIUM IN AIRCRAFT

DEFENSE METALS INFORMATION CENTER
BATTELLE MEMORIAL INSTITUTE
COLUMBUS, OHIO

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SUMMARY

Historically, titanium and its alloys have been proven capable of performing efficiently and satisfactorily in both airframe and aircraft gas-turbine engines. Nevertheless, under certain conditions, titanium and its alloys are known to be capable of ignition and combustion. This note was prepared to review the conditions under which the ignition and combustion of aircraft components were most likely to occur as well as to assess the actual incidences of such fires.

Laboratory tests have shown that sheets of commercially pure titanium and several of its alloys can be ignited in air using an oxyacetylene torch and heating these materials to their melting temperatures (about 3000 F). The sensitivity of titanium toward ignition and combustion in oxygen atmospheres increases with increasing oxygen pressure and concentration such that with sufficiently high pressures and concentrations, burning can occur at appreciably lower temperatures.

Once ignited, titanium sheet will continue to burn in the presence of a high-velocity air stream. Also, at least superficial burning has been observed on titanium components which have been subjected to moderate temperatures and high-rubbing-velocity friction loads in air. Similarly, it has been shown that a thermite reaction can be initiated and propagated on an unheated, 0.025-inch-thick sheet of the Ti-6Al-4V alloy by subjecting this material to molten droplets of mild steel in the presence of a high-velocity air jet. Finally, the sliding friction of titanium on bare or foamed runways can be expected to cause significant friction sparking of titanium. The resulting sparks can ignite fuel mists.

Reports were received of 8 aircraft gas-turbine fires involving titanium components in US-produced engines and in 5 engines produced in Canada or England. While details on many of these experiences are lacking, the available information suggests most of these fires were caused either by the rubbing friction of titanium parts (due to improper parts design and/or service failures of other components) or by the service failure of other components, i.e., sparking of steel rotor blades and a subsequent thermite reaction.

No authenticated reports of any fires involving titanium airframe structures were received.

INTRODUCTION

Historically, titanium and its alloys have proven capable of performing efficiently in a variety of airframe as well as aircraft gas-turbine engine applications. Thus, unalloyed titanium sheet as well as a number of its alloys have been used as skin material in selected areas, as structural elements and as crack stoppers in airframe and fuselage construction as well as for firewall construction. Also, hundreds of engines incorporating titanium alloy components in the compressor stage and subjected to temperatures through 700 F have aggregated thousands of hours of satisfactory service.

Nevertheless, under certain conditions, titanium and its alloys are capable of ignition and combustion. This technical note attempts to identify the laboratory and service conditions under which the ignition and combustion of simulated or real titanium aircraft components either is likely to occur or has actually occurred. It is based, in part, on the following earlier Defense Metals Information Center memoranda:

DMIC Memorandum 89, "Summary of Present Information on Impact Sensitivity of Titanium When Exposed to Various Oxidizers", March 6, 1961

DMIC Memorandum 163, "Reactivity of Metals With Liquid and Gaseous Oxygen", January 15, 1963.

This note also summarizes information obtained recently by phone, letters, and/or personal interviews with two of the leading airframe producers and all of the US aircraft gas-turbine engine manufacturers, as well as a number of US Government Agencies including the US Air Force.

This note does not discuss in detail the reactivity of titanium with liquid oxygen or the impact sensitivity of titanium in the presence of oxygen and other oxidizers. Hence, it should be regarded as a supplement to, rather than as a substitute for, the two DMIC memoranda listed above. Neither does this note concern the fire and explosive hazards associated with the preparation or handling of titanium sponge, powder, scrap, and ingots, or with the preparation of mill products. For the record, DMIC notes that extensive studies in this area have resulted in the adoption of certain standards(1)* which have been widely accepted.

THE IGNITION AND COMBUSTION CHARACTERISTICS OF MASSIVE TITANIUM

A number of laboratory and field tests have been conducted to explore the conditions under which massive titanium metal components can be ignited and made to burn. Most of these studies were intended to simulate conditions which might arise from malfunctions in aircraft, engines, or their supporting structures. These experiences are conveniently discussed according to whether the test environment consisted of air or oxygen-rich gaseous mixtures.

Air Environment

The experiences reported to date have generally shown that, in the absence of molten iron oxide,(a)

* References cited are appended at the end of this note.

(a) Thermite reactions of titanium with iron oxide are discussed separately below.

massive titanium cannot be ignited in ordinary air atmospheres without the application of an external source of heat. Further, these experiences suggest that even with the application of heat, flame or metal temperatures approaching the melting point of the metal (about 3000 F) are necessary for ignition to occur.

Torch-Heating Experiments

Several investigations[2,3] performed in the early 1950's established the usefulness of titanium as a material for aircraft firewall construction, an application in which titanium continues to serve today in a variety of military and civilian aircraft. To the knowledge of DMIC, the acceptance of titanium for this application is based on a number of independent laboratory tests which demonstrated its ability to resist ignition and combustion on exposure in air to flame temperatures up to and including 2000 F.

The Civil Aeronautics Administration is among the various groups which have evaluated titanium for this application.[3] In this particular study, tests were performed on three grades of commercially pure titanium and the Ti-5Al-2.5Sn alloy to determine their strength to 1800 F and their resistance to a 2000 F flame. The tensile tests showed that, as would be expected, the strengths of all the titanium sheet materials decreased rapidly with increasing temperatures above 1000 F. In the flame tests, 24 x 24-inch sheets of these materials were exposed for 15 minutes to a 2000 F flame from an oil burner which consumed 2 gallons of kerosene per hour. The flame contact area was elliptical in shape, having major and minor axes of 12 and 6 inches, respectively. Tests were conducted under the following conditions:

(1) equal pressure on each side of the firewall

(2) a 5-psi pressure differential across the firewall, and

(3) a 15-psi pressure differential.

None of the titanium materials ignited in these tests and the specimens tested under no load "served as an effective firewall". However, considerable distortion occurred to the specimens tested under a 5-psi pressure differential and a 15-psi pressure differential caused failure in two specimens.

At least one report is available which attests to the satisfactory inflight performance of a titanium firewall. Thus, in 1957, the Douglas Aircraft Company reported[4] that "a...practical test of the ability of this..."(titanium firewall)"material to resist fire occurred in December, 1955, when a DC-7 aeroplane operating out of Rome, Italy, experienced a fire on its Number 3 engine".

Several studies have shown that sheet titanium can be ignited by heating the metal in air to high temperatures. Westinghouse,[5] for example, observed that 0.125-inch-thick strips of unalloyed titanium were ignited by torch heating the metal to its melting range. On removing the flame, burning ceased almost immediately, even in the presence of a blast of shop air or pure oxygen.

Similar results were obtained in early tests at Douglas,[6] using self-resistance heating methods for five thicknesses of sheet (0.016-, 0.020-, 0.025-, 0.032-, and 0.040-inch) and one diameter of wire (0.0625 inch), all of commercially pure titanium. In this case, after reaching the desired temperature, the materials were subjected to an air or oxygen blast from a 3/16-inch-diameter jet situated perpendicular to the surface of the specimen at a distance of 1/2 inch. The ignition behavior of these materials as a function of thickness and air velocity is summarized in Figure 1. No difference in ignition temperatures was found when oxygen was substituted for air in the impinging jet. It was concluded that "the spontaneous ignition temperature of commercially pure titanium sheet and wire in an air or oxygen stream at 470 and 680 ft/sec...(was) in excess of 3000 F."

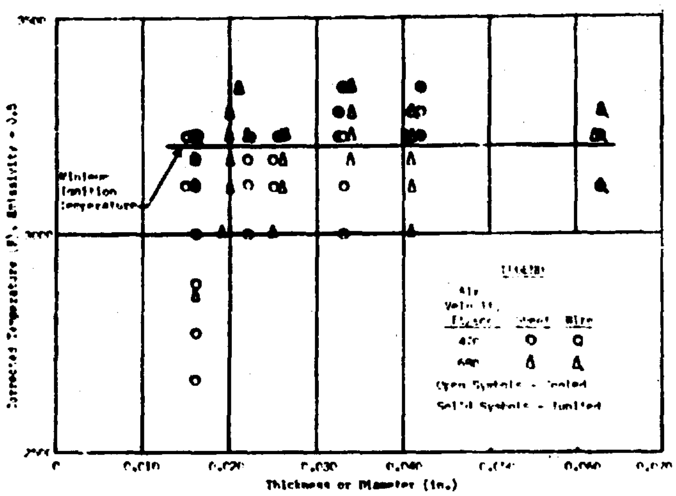

FIGURE 1. IGNITION BEHAVIOR OF TITANIUM AS A FUNCTION OF THICKNESS AND AIR VELOCITY[6]

Later tests at Douglas[7] showed that, once ignited, burning in a 0.025-inch-thick sheet of the Ti-6Al-4V alloy could be propagated by an air blast of considerable velocity. In this work, ignition was again achieved by melting the material with an oxygen acetylene torch. Compressed air at 90 psi was then directed through a 1/8-inch nozzle held 2 inches from the heated area and parallel to the surface of the sheet. With the air jet in this position, burning continued after removal of the flame. However, moving the air jet more than a distance of 2 inches away from the melted titanium would not cause continuation of the burning, which would stop immediately on removal of the air jet.

The effects of air and oxygen at moderate pressures and velocities on the ignition characteristics of titanium were also studied at Stanford University.[8] In one set of conditions, strips of unalloyed titanium and two alloys were resistance heated in a tank containing air or oxygen at pressures up to 7 atmospheres. Table 1 lists the materials and thicknesses evaluated and the ignition temperatures determined under these conditions. As indicated, ignition of all of these materials was observed at temperatures of 2850 F or greater in air or oxygen. No effect of thickness was observed. No appreciable differences between the ignition temperature in air and oxygen were found although it was noted that "the rate of burning after ignition was considerably greater with oxygen than with air". The same materials were also subjected to free-jet wind-tunnel tests in which air, at a

velocity of Mach 1.25 was discharged through an area of 0.76 square inch against the electrically heated sample materials. The ignition temperatures determined under these conditions were substantially the same as those given in Table 1.

TABLE 1. IGNITION TEMPERATURES OF TITANIUM SHEET IN PRESSURIZED ATMOSPHERES[8]

Material	Sheet Thickness, inch	Ignition Temperature, F[a]	Gas	Pressure, atm
RC 70 (CP Ti)	0.010-0.067	2880 to 2960	Air, O_2	1 to 7
RC 70 (CP Ti)	0.025	2890 to 2940	Air, O_2	1 to 7
RS-110A (Ti-8Mn)	0.025	2860 to 2910	(b), O_2	1 to 7
RS-110BX (Ti-8Mn-1.5Al)	0.025	2850 to 2920	(b), O_2	1 to 7

(a) "Brightness" temperatures, determined optically.
(b) Melted, but did not ignite, in air at temperatures of 3260 ± 100 F and pressures of 1 to 7 atmospheres.

Friction Heating and Spark Ignition Studies

Westinghouse[5] has described two laboratory studies to investigate the ignition tendencies of titanium under frictional contact.

In the first of these, titanium strips (approximately 0.125-inch-thick) were heated to 1200 F and 1400 F in a laboratory muffle furnace, then pulled out and subjected to "grinding" with a tool steel burr operated at 10,000 rpm. At neither of these temperatures was any "significant effects" produced. The 1400 F tests were then repeated using a blast of shop air and an oxygen-rich oxyacetylene flame in separate attempts to promote ignition. Again, there was no evidence of an increased tendency for the titanium to ignite.

The second series of tests utilized a spin rig which was fitted with a pneumatic actuator that pressed two titanium shoes, 180 degrees apart, against a rotating disc (of unidentified material). The actuator was operated by a solenoid air valve that allowed the shoes to be extended and withdrawn. The shoe temperature was recorded at the test operating speed with the shoes withdrawn. In the tests employing heated shoes, only one of the two shoes was heated. A table of the test conditions follows:

Run No.	Disc Speed, rpm	Actuator Air Pressure, psi	Shoe Temperature
1	10,100	75	Room, Amb.
2	14,000	75	Room, Amb.
3	14,000	35	Room, Amb.
4	14,000	35	380 F
5	14,000	35	480 F

"Runs 1, 2, and 3 produced considerable sparking but showed no evidence of fire. The shoes evinced only the grooves produced by rubbing on the disc rim. In Run 4, the heated shoe continued to glow for about 3 seconds after withdrawal. The perimeters of the rubbing grooves were irregular and showed evidence of local melting... In Run 5, the heated shoe continued sparking and maintained a strong glow for 5 seconds after withdrawal. The rubbing grooves were completely burned away." It was concluded that "titanium has the ability to support combustion when it is used in certain conditions that could occur in an engine, such as moderate ambient temperatures, and high-rubbing-velocity friction loads. It would seem reasonable to assume that as the ambient temperature increases, the probability of a fire would increase."

Two other separate studies[9,10] were made to explore the spark ignition tendencies of titanium under aircraft crash conditions. In both cases, it was shown that significant friction sparking would result from the sliding friction of titanium on bare or foamed concrete runways. Also, the sparks resulting from the friction of titanium on concrete and asphalt runways can ignite fuel mists, including gasolene, kerosene, JP-4 fuel, and preheated SAE No. 5 lubricating oil.[9] However, no reports were found to indicate that such conditions would ignite thin titanium skin sheaths.[11]

Thermite Reactions

To the knowledge of DMIC, no exhaustive study of titanium thermite reactions has been made. However, a reaction of this type between heated titanium and iron oxide has been known to exist since at least 1953. Harvey Aluminum Incorporated has observed that the ignition and reaction of titanium alloy ingots in contact with iron oxide can occur at temperatures as low as 2200 F.[12] Furthermore, laboratory tests performed by the Douglas Aircraft Company[7] have shown that a thermite reaction can be initiated and propagated on an unheated, 0.025-inch-thick sheet of the Ti-6Al-4V alloy by subjecting this material to molten droplets of 1020 steel in the presence of a high-velocity air jet. In this work, the steel was placed 6 inches above the titanium alloy and compressed air at 90 psi was directed parallel to the titanium alloy through a 1/8-inch nozzle held approximately 3 inches from the molten steel drops.

Some earlier test experiences of Rolls-Royce, Limited are also of interest. These arose from a localized flame-tube failure which allowed a jet of combustion gases to be directed on a main engine support which passed within a few inches of the flame tube. The result was that the mild-steel engine support was burned approximately in half. The following engine test was made to learn what happened and to develop a fix:

1. Baseline: a ruptured combustor, similar to the original failure, was fitted to an engine and within 29 seconds, the field failure was duplicated in the Rolls house engine.

2. Configuration 1: flame/titanium shield[a]/1/16-inch space/engine support. After 10 minutes, the titanium was discolored but it afforded ample protection to the engine support.

(a) Commercially pure titanium sheet, 0.048-inch thick.

3. Configuration 2: flame/double titanium shield(a)/1/16-inch space/engine support. Protection was even more satisfactory than Configuration 1.

4. Configuration 3: flame/stainless steel/1/8-inch asbestos/titanium shield(a)/1/4-inch space/engine support. A rapid thermite-type disintegration took place resulting in several square inches of the stainless steel and titanium shield being consumed. The throttle was chopped when the burning started and "burning ceased in the instant that followed, when observation was obstructed by smoke and flames".

Subsequent additional laboratory tests were performed with unalloyed titanium shields 7 inches long with a half-circle diameter of two inches. Here, flame impingement times of 10 to 15 minutes did not effect the shield, which provided complete protection to the strut. However, when a mild-steel sheet was interposed between the shield and the flame source, a thermite-type reaction was initiated by oxide splatter from the steel. This resulted in burn-through of the titanium shield at the areas contacted by oxide splatter. Similar results were observed when a stainless steel/asbestos/titanium sandwich shield was heated.

Environments of Gaseous Oxygen and Oxygen-Rich Mixtures

Several of the investigations cited in the previous section of this note indicated that the substitution of pure oxygen for air at moderate pressures (to 7 atmospheres, Ref. 8) or velocities (to 680 ft/sec, Ref. 6) had no significant effect on the autoignition temperature of titanium. However, as pointed out earlier, the Stanford University(8) work showed that when oxygen pressures of 1 to 7 atmospheres were used in place of air, the rate of burning was considerably greater.

Aerojet-General(13) has since shown that the autoignition temperature of titanium is significantly decreased at increasing pressures of oxygen. Here, resistance-heated tubes were placed in a pressure chamber. Thermocouples, inside the tubes, were used to measure temperature. In 50 psig oxygen, ignition occurred about 250 F below the melting point ("about 3000 F"), while with 300 psig oxygen, ignition occurred about 1000 F below the melting point.

In early 1959, attention was drawn to the violent reactions which can be initiated on the exposure of titanium to liquid oxygen. Since that date, considerable study has been devoted to the factors necessary to promote reactions between titanium and liquid oxygen as well as gaseous oxygen. Most of the information available to DMIC from this work was discussed in DMIC Memorandum 163. As indicated there, these studies are primarily concerned with conditions that would be encountered in missile and space service. However, it is conceivable that some of these conditions might also be encountered in advanced aircraft. For this reason, it was deemed advisable to reproduce below those portions from the summary of DMIC Memorandum 163 concerning titanium.

Of all the metals studied to date, titanium exhibits the greatest sensitivity to impact when immersed in LOX. In fact, its sensitivity approaches that of many organic materials such as greases and oils. Reactivity is observed in liquid oxygen and mixtures of liquid oxygen and liquid nitrogen at 20 ft-pounds until the LOX concentration is reduced to 30 per cent. Titanium can be partially protected from reactivity in LOX under impact by certain protective coatings, provided the coatings are not broken. Protection is given by electroless copper and nickel, possibly aluminum, and to a lesser extent by Teflon and a fluoride-phosphate coating. Protection is also obtained by nitriding which adds a protective film to the surface, and by annealing which increases the thickness of the oxide film.

Titanium exhibits no great reactivity in LOX when deformed by compression, by exposure of a fresh surface by machining or rupture, or by exposure of bulk titanium to high-pressure or high-velocity LOX.

In gaseous oxygen, titanium is highly reactive when a freshly formed surface is exposed at even moderate pressures. Under conditions of tensile rupture, a pressure of about 100 psig will initiate a violent burning reaction with titanium from about -250 F up to room temperature. Above room temperature, the pressure required to initiate the reaction is decreased somewhat. When 2 per cent HF is added as an inhibitor or 5 per cent argon as a diluent, the pressure must be increased about twofold at room temperature before reaction occurs. Titanium could not be made to react even at very high pressure when oxygen content was 35 per cent or less.

When a titanium vessel containing LOX or gaseous oxygen is ruptured by a bullet, by a simulated micrometeoroid, or by other mechanical puncture, violent burning begins at almost 0 psig. If the vessel is not fractured by external impact, vibration, acoustic energy, thermal effects, or with slowly propagated cracks, such as fatigue cracks, no reactivity is noted.

When bulk titanium is heated in high-pressure oxygen, ignition and burning will occur at a temperature somewhat below its melting point. Similar reactions have been noted in CO_2. Ignition of titanium is also initiated under conditions of explosive or electrical shock.

The mechanism for the Ti-O_2 reaction is described as a reaction between a freshly formed titanium surface and gaseous oxygen.

For additional details on the above experiences, the reader is referred to DMIC Memorandum 163.

INCIDENCES OF REPORTED TITANIUM FIRES IN AIRCRAFT

In general, the only information disclosed to DMIC concerning fires in titanium aircraft components related to aircraft gas-turbine engines on test stands. One report was received that a current commercial passenger transport, which utilizes titanium extensively in its jet engine pods, had suffered an engine fire in which titanium components were

(a) Commercially pure titanium sheet, 0.048-inch thick.

"dramaticlily involved". Subsequent efforts to verify this report with the aircraft manufacturer proved fruitless.

A resumé of the reported experiences with fires in jet engines is given as follows.

US Experiences

Westinghouse Electric Corporation

Westinghouse, who has since discontinued the manufacture of aircraft jet engines, disclosed(5) experiences with fires in three engines in the period around 1956.

Two fires were reported in engines constructed with titanium rotor and stator blades and a titanium compressor case. These fires occurred on the test stands and were secondary failures. Thus, in one instance, rubbing together of titanium parts resulted when a bearing collapsed. In the second instance, a braze joint failed, causing friction which initiated the second fire.

Another fire occurred in a test-stand engine which incorporated a titanium turbine housing and titanium 1st- and 2nd-stage turbine liners. Extensive damage occurred to the 1st- and 2nd-stage blades and nozzles, turbine housing and liners, combustor housing and outer liner, and exhaust collector housing and innnr cone. In the final analysis, the probable cause of the burnout was assumed to be an unfortunate combination of conditions existing in the turbine that resulted in actual ignition and sustained combustion, for a short time, of the titanium liners and housing.

Though not definitely established, indications were that a fuel fire may have occurred in an area outside the turbine housing, as a result of fuel leakage from the combustor. Buckling of the housing and a resultant severe blade rub on the titanium liner could then have occurred. The combination of excessive temperatures from the fuel fire, frictional heating from the blade rub, and perhaps the introduction of fine titanium powder into the area from the blade rub could very likely have ignited the more massive titanium housing, and also served to sustain combustion for a short time. "It is also possible that the attempt to extinguish the fire with CO_2 actually prolonged combustion, since it was later learned from the literature that CO_2 does tend to intensify titanium fires."

As a result of this occurrence, the decision was made to discontinue the use of titanium turbine liners.

Also, during tests in early 1958 of a Tyne HP compressor, Westinghouse observed that rubbing of steel stator tips against steel rotor disks caused hot steel particles to fly downstream against a series of "titanium" rotor blades. "Severe thermite-type burning of some blades resulted."

Company A

This company had experienced one fire in a "titanium compressor" of a jet engine on a test stand. Details of the cause of fire were withheld as proprietary.

Company B

"Two or three" fires have occurred in compressors of engines during testing. The cause of these fires was rubbing of titanium on titanium, as a result of a prior failure. These fires occurred in compressors using rotor and stator blades of a thin section, honeycomb design. The contact stated that the fire hazard was eliminated by design changes to replace the thin section components with parts having thicker sections.

Foreign Experiences

Canada

A report was received of fires in three engines being tested in the period 1956-1957. So intense was the heat from each fire that all parts of the compressor sections were totally destroyed. These engines were experimental models and had titanium rotor and stator blades, titanium stator rings, a titanium compressor case, and Type 17-22 stainless steel shafts.

An investigation was made but no satisfactory explanation for the cause of the fires was found. The rationalized cause of the fires was rubbing of titanium rotor blades on the adjacent titanium stator. The titanium stator blades and rings were replaced with stainless steel and the titanium compressor case replaced with a magnesium-thorium alloy. The titanium rotor blades were not replaced. Although rubbing of rotor blades on the steel stator occurred more frequently than in the engine with titanium stators, no fires resulted.

Great Britain

The following information was extracted from British Overseas Airways Corporation Headquarters Fire Bulletin No. 69 (undated):

"Avon engines on Comets and Conway engines on Boeing 707's have titanium stator and rotor blades at certain stages in the compressor section. In two cases with Avon engines, fires have occurred involving the titanium, following blade failure and resultant friction leading to melting and ignition of the metal...Following the two fires, one during ground taxi-ing and one on engine test beds, detailed investigation and tests were carried out by BOAC and Rolls-Royce to determine the extent of the titanium problem and the possibility of any magnesium alloy in the compressor casing being ignited. From these tests, it can be stated that in the remote event of a blade fire, the titanium blades will be burned out in under one minute. High temperatures will be involved, and there may be considerable secondary fire damage to the engine, but tests have shown that the mass of the magnesium casing, coupled with its relatively high thermal conductivity, is sufficient to prevent burning, although localized melting and embrittlement may arise. Due to the high melting point of titanium (1800 C), considerable radiant heat will be produced and take a long time to dissipate."

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